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MONOTONIC AND LOW-CYCLE FATIGUE RESPONSE OF A MARAGING STEEL AND METASTABLE BETA TITANIUM ALLOY UNDER TORSIONAL LOADING

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ENGINEERING STANDARDIZATION DIVISION

February 1977

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ABSTRACT

This study deals with the torsional response of Ti-8823 and 18Ni (200) maraging steel. The effect of different heat treatments and the subsequent change in microstructure are investigated. In the case of the Ti-8823, a comparison was made between the solution-treated-and-aged condition, and the direct-aged condition. It was found that the finer precipitate morphology in the DA material offered a greater resistance to torsional fatigue. For the 18Ni (200) maraging steel, an increase of aging time from 3 to 98 hours led to a substantial increase in the amount of reverted austenite, which in turn led to a significant improvement in torsional fatigue behavior. The results are analyzed in terms of the Manson-Coffin equation.

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INTRODUCTION

Much of the designer's information is based on a material's response to tensile deformation. However, when service requirements are clearly nonuniaxial, it behooves the designer to obtain information which more closely approximates service loading conditions. Designing components to carry torsional loads such as with torsion bars is an example. Torsional loading has been accompanied by nonuniform deformation which is unlike that observed under tensile loading.[1-3] For example, the 18Ni maraging steel family exhibits an excellent combination of toughness, strength, and ductility. Here, strength and ductility refer to behavior under tensile loading. However, under torsional loading 18Ni maraging steels compared to other high strength steels shows a marked decrease in strain to fracture.[3] This report examines aspects of the torsional deformation of 18Ni (200) maraging steel which may improve its performance under monotonic as well as strain-controlled torsional fatigue loading.

Strength values in the range provided by the 18Ni (200) maraging steel are also possible with metastable beta titanium alloys. However, there appears to be little data in the literature regarding behavior of these titanium alloys under either monotonic or cyclic torsional loading. Therefore, the present effort also concerns itself with the metastable beta titanium alloy Ti-8Mo-8V-2Fe-3Al, henceforth termed Ti-8823.

MATERIALS AND TEST PROCEDURE

The chemical composition for the 18Ni (200) and Ti-8823 alloys are shown in Table 1. The heat treatments that were utilized are detailed in Table 2. The Ti-8823 was given either the generally recommended solution treatment and age (STA) heat treatment or direct age (DA) after hot work. The heat treatment for 18Ni (200) steel includes a treatment that provides substantial amounts of reverted austenite. This treatment was used by Pampillo and Paxton[4] to improve the tensile properties. The amount of reverted austenite present in the material after this heat treatment was determined by X-ray diffraction analysis to be approximately 37 percent.

Solid cylindrical specimens approximately 0.200 inch in diameter were tested in a 2000 in.-lb Instron torsion machine. Monotonic torque-twist curves were obtained from each heat-treated condition. In addition, strain-controlled low-cycle fatigue tests were conducted in torsion to obtain the plastic shear strain range ($\Delta\gamma_p$) versus number of cycles to failure (N_f) curves. A cyclic strain hardening exponent n' was obtained from a least-squares fit of the log-log plot of the shear stress versus shear strain utilizing stress values obtained from steady-state hysteresis loops at different $\Delta\gamma_p$ levels.

1. POLAKOWSKI, N. H., and MOSTOVOY, S. *Transient and Destructive Instability in Torsion.* Trans. ASM, v. 54, 1961, p. 567.
2. SPRETNAK, J. W. *Plastic Instability in Some Ultra-High Strength Steels.* Trans. Japan Institute of Metals, v. 9, 1968, p. 305.
3. CHAIT, R. *Flow and Fracture of High Strength Steels in Torsion.* J. Test and Evaluation, v. 1, 1973, p. 435.
4. PAMPILLO, C. A., and PAXTON, H. W. *The Effect of Reverted Austenite on the Mechanical Properties and Toughness of 12Ni and 18Ni(200) Maraging Steels.* Met. Trans., v. 3, 1972, p. 2895.

Table 1. CHEMICAL COMPOSITION (WEIGHT PERCENT)

Alloy	Ni	Co	Mo	Ti	Al	Mn	Si	P	S	C
18Ni (200) Steel	18.3	8.5	3.22	0.22	0.08	0.04	0.04	0.005	0.008	0.008
	Al	V	Mo	Fe	Sn	Cu	C	O	H	N
Ti-8823	3.08	8.08	7.80	2.07	-	-	0.035	0.133	0.006	0.010

Table 2. HEAT TREATMENT OF MARAGING STEEL AND TITANIUM ALLOY

Alloy	Austenitizing or Solutionizing Treatment	Aging Treatment	Comment
18Ni (200)	1500 F(1 hr)	900 F(3 hr)	Customary heat treatment
	1500 F(1 hr)	968 F(98 hr)	Reverted austenite heat treatment
Ti-8823	1475 F(1-1/2 hr)	1000 F(8hr)	STA heat treatment
	-	950 F(8 hr)	DA heat treatment

RESULTS AND DISCUSSION

Torsional Stress-Strain Curve (Monotonic)

The monotonic shear stress-shear strain curves for 18Ni (200) and Ti-8823 alloys are shown in Figures 1 and 2. From these curves, strain hardening differences were determined since it has been shown that one of the factors influencing torsional ductility is the strain hardening behavior. In their work with 2024 aluminum Fields and Backofen[5] have shown that a low strain hardening rate is a contributing factor to the occurrence of nonuniform torsion deformation. The 18Ni (200) steel given the customary heat treatment displays a definite tendency toward localized deformation upon monotonic loading as shown in Figure 3. As expected, the presence of the localized deformation reduces the strain to fracture. Using a power-law relationship $\tau = K\gamma^n$ between the shear stress τ and shear strain γ, the strain hardening exponent n of 18Ni (200) steel given the customary heat treatment is approximately 0.05. The 18Ni (200) steel given the reverted austenite heat treatment exhibits a stress-strain curve where $n \approx 0.07$. In line with this trend is the fact that the material given the reverted austenite heat treatment exhibited a greater value of strain to fracture without a decrease in strength.

The same trend is seen with the Ti-8823 material. For the material given the DA heat treatment, $n \approx 0.11$, while the STA heat treatment leads to $n \approx 0.05$. Therefore, it is not unexpected that the strain to fracture for the DA material is greater than for the STA material at about the same shear strength level.

It was mentioned that the enhancement of torsional ductility in the 18Ni (200) steel was due to the presence of reverted austenite and its effect on the material's capacity to strain harden. Microstructural differences also exist for Ti-8823. As shown in Figure 4, material given the age treatment directly after hot working shows a fine, uniformly distributed network of alpha particles,

5 FIELDS, D. S., and BACKOFEN, W. A. *Determination of Strain Hardening Characteristics by Torsion Testing.* Proc. ASTM, v. 57, 1957, p. 1259.

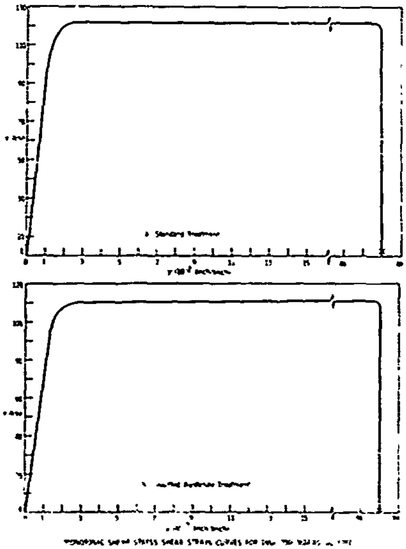


Figure 1. Monotonic shear stress-shear strain curves for 18Ni (200) maraging steel.

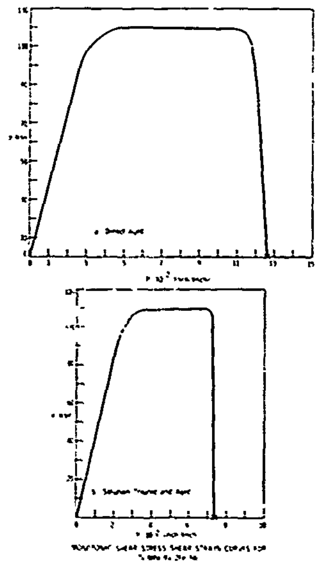


Figure 2. Monotonic shear stress-shear strain curves for Ti-8Mo-8V-2Fe-3Al.

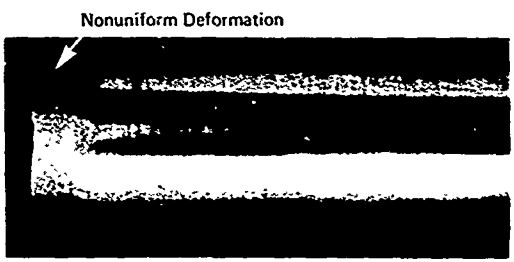


Figure 3. Localized torsional deformation of 18Ni (200) maraging steel as a result of monotonic loading. Mag. 4½X.

Direct Aged

Solution Treated and Aged

Figure 4. Effect of heat treatment on microstructure of Ti-8823 alloy. Mag. 12,000X

whereas material given the STA heat treatment possesses alpha precipates which are coarse compared to DA material. This is due to the effect of the intermediate solutionizing treatment.[6] It is interesting to note that DA microstructure also results in better fracture toughness, yield strength, tensile strength, and tensile ductility than the STA material.[6]

Torsional Low-Cycle Fatigue Behavior - $\Delta\gamma_p$ Versus N_f Curves

Factors that influence the monotonic torsional stress-strain curves would also be expected to have a pronounced effect on the low-cycle fatigue behavior. The torsional low-cycle fatigue test results are shown in Figures 5 and 6 where $\Delta\gamma_p$ (plastic strain range) is plotted as a function of N_f (cycle to failure) for both Ti-8823 and 18Ni (200) steel. For Ti-8823, there is a marked difference between the DA and STA materials. For a given strain range, the DA material exhibits a higher N_f. The same is true for the 18Ni (200) steel given the reverted austenite heat treatment.

Visual observations made during the cycling of the 18Ni (200) steel show the higher resistance to torsional deformation of the material given the reverted austenite heat treatment. Localized deformation bands shown in Figure 3 provide sites for surface cracks of the type shown in Figure 7a during deformation of the material given the customary heat treatment. While material given the reverted austenite heat treatment does have some cracks as shown in Figure 7b, they are less numerous than those shown in Figure 7a for regularly heat-treated material, despite the order of magnitude difference in $\Delta\gamma_p$.

6. CHAIT, R., and DeSISTO, T. S. *An Evaluation of Some High Strength Titanium Alloys Processed in Heavy Section.* Army Materials and Mechanics Research Center, AMMRC PTR 75-3, September 1975.

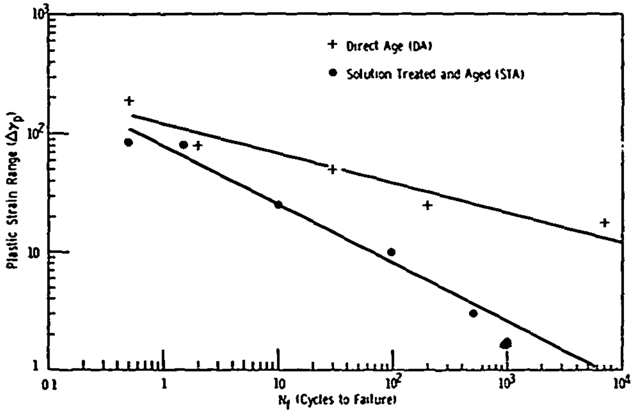


Figure 5. Low-cycle fatigue curves for Ti-8823.

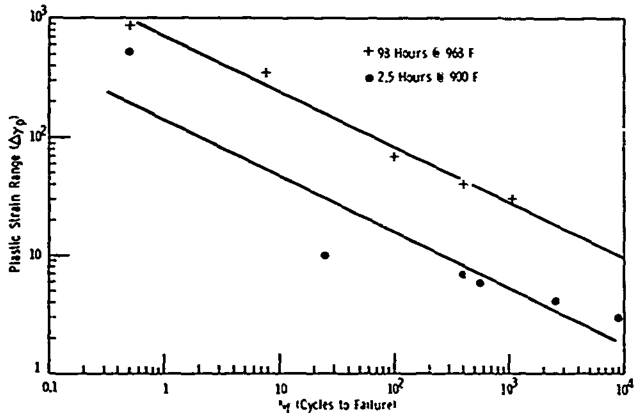
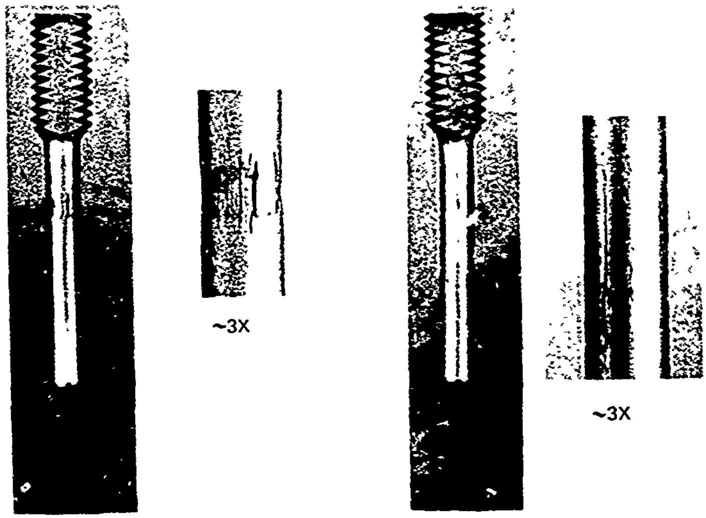


Figure 6. Low-cycle fatigue curves for 18Ni (200) maraging steel.



a. Regular heat treatment (after 550 cycles, $\Delta\gamma_p = 0.006$)

b. Reverted austenite (after 400 cycles, $\Delta\gamma_p = 0.05$)

Figure 7. The effect of heat treatment on crack formation of 18Ni (200) maraging steel after torsional fatigue.

Analysis of Low-Cycle Fatigue Behavior

Efforts to characterize the low-cycle fatigue behavior are well known.[7] It was found that tensile low-cycle fatigue behavior can be described by

$$N_f^{1/2} \, \Delta\epsilon_p = \text{constant} \qquad (1)$$

where $\Delta\epsilon_p$ is the plastic strain range.

A more general form of the equation was obtained by Feltner and Morrow.[8]

$$N_f^{c} \, \Delta\epsilon_p = \text{constant} \qquad (2)$$

Here, the damage energy is considered to result primarily from plastic work and is assumed to be constant. Assuming an exponential relationship between plastic stress and plastic strain, one arrives at

$$c = -(1/1+n) \qquad (3)$$

7. TAVERNELLI, J. F., and COFFIN, L. F., Jr. *A Compilation and Interpretation of Cyclic Strain Fatigue Tests on Metals.* Trans ASM v. 51, 1959 p. 438
8. FELTNER, C. E., and MORROW, J. D. *Microplastic Strain Hysteresis Energy as a Criterion for Fatigue Fracture.* Journal of Basic Engineering, March 1961, p. 15

where n is the strain hardening exponent. Halford and Morrow[9] took the plastic zone size into account and obtained

$$c = -(1/1+5n) \tag{4}$$

Equation 4 was also utilized to analyze the torsional low-cycle fatigue behavior of several alloys, both ferrous and nonferrous.[9] Using strain hardening exponent values obtained from monotonic torsion tests, satisfactory agreement was obtained between the measured and actual slope of the $\Delta\gamma_p$ versus N_f curves. It was noted that perhaps one should use the strain hardening exponent representative of cyclic behavior (n') rather than monotonic behavior.[10] In the present study both n and n' were utilized in conjunction with Equation 4 to calculate the slope of $\Delta\gamma_p$ versus N_f curves and compare it with the value obtained from the actual slope. From the comparison shown in Table 3, it is seen that utilizing n' values results in better agreement.

Table 3. COMPARISON OF ACTUAL AND CALCULATED SLOPES OF $\Delta\gamma_p$ VERSUS N_f CURVES

Materials	Heat Treatment	n	n'	Measured Slope	Calculated Slope -(1/1+5n)	Calculated Slope -(1/1+5n')
Ti-8823	STA	0.05	0.123	-0.48	-0.80	-0.62
	DA	0.11	0.11	-0.26	-0.64	-0.65
18Ni (200)	Reverted Austenite	0.07	0.13	-0.47	-0.74	-0.60
	Regular	0.05	0.13	-0.55	-0.93	-0.61

NOTE: n and n' are the values of the strain hardening exponents obtained from monotonic and cyclic tests, respectively.

CONCLUSION

This study has examined the torsional response of two high strength alloys, an 18Ni (200) maraging steel and a Ti-8Mo-8V-2Fe-3Al alloy. Both monotonic and low-cycle fatigue behavior were examined. The following conclusions were made.

1. Compared to 18Ni (200) steel given the customary heat treatment, increasing the amount of reverted austenite improves resistance to torsional deformation under monotonic as well as low-cycle fatigue loading.

2. Direct aging after hot working provides Ti-8823 with better resistance to torsional deformation (both monotonic and low-cycle fatigue) than does the more common solution-treat-and-age heat treatment.

3. These improvements are thought to be associated in part to increased strain hardening capacity.

4. The low-cycle fatigue behavior can be analyzed using the representation of Halford and Morrow. Good agreement was obtained between calculated (using cyclic strain hardening values) and measured values of the slope of the $\Delta\gamma_p$ versus N_f curves.

9. HALFORD, G. R., and MORROW, J. D. *Low Cycle Fatigue in Torsion.* Proc. ASTM, v. 62, 1962, p. 695.
10. VAN SWAM, L. F., PELLOUX, R. M., and GRANT, N. J. *Fatigue Behavior of Maraging Steel 300.* Metallurgical Transactions A, v. 6A, January 1975, p. 45.

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